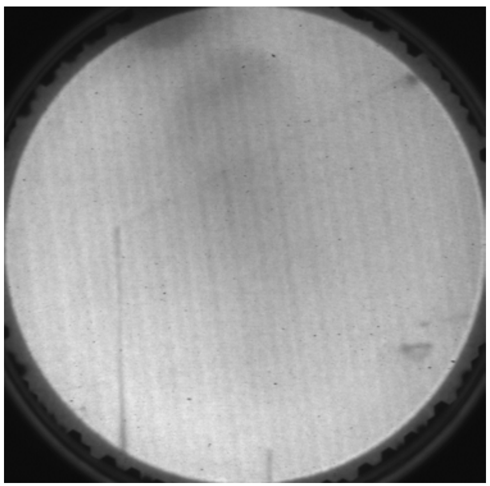
Element Specific Imaging of Magnetic GaMnN

Lian Li, University of Wisconsin, Milwaukee, DMR-0094105

Photoemission electron microscopy (PEEM), conducted on a synchrotron beam line (Advanced Photon Source), allows the excitation energy to match element-specific x-ray absorption edges. The emission of element-specific electrons can then be recorded to produce an image of the spatial distribution of the chemical species.



PEEM image taken on the absorption edge of Mn for a $Ga_{0.95}Mn_{0.05}N$ sample.

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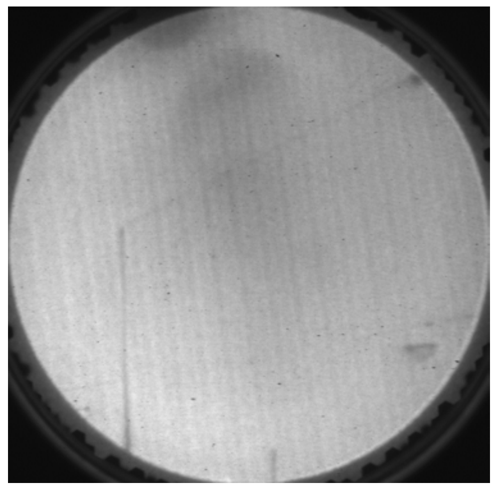

Image taken just below the Mn absorption edge.

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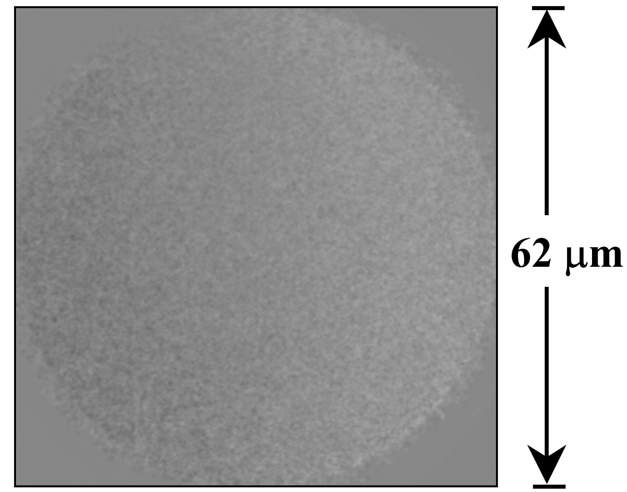

Differential image, showing the spatial distribution of Mn is uniform.

What: Mn-doped GaN, a ferromagnetic semiconductor (FMS) has great potentials for spintronic devices.

So What: Practical device applications require homogeneous materials. Here it is shown that the spatial distribution of Mn is uniform for this $Ga_{0.95}Mn_{0.05}N$ sample with the 100 nm resolution of the microscope. In addition, thorough high-resolution TEM experiments on samples identically grown reveal no nm-scale features and areas of localized Mn concentration.

We have studied the homogeneity of a ferromagnetic semiconductor (FMS), GaMnN, using a technique with chemical specificity. Photoemission electron microscopy, conducted on a synchrotron beam line (Advanced Photon Source (APS), Argonne National Lab), allows the excitation energy to match element-specific x-ray absorption edges. The emission of element-specific electrons can then be recorded to produce an image of the spatial distribution of the chemical species. By taking an image on the absorption edge of Mn (left image), and subtract background contributions obtained by taking another image over the same area just below the Mn absorption edge (middle image), a spatial distribution of this element is obtained (right image). There are no microscopic features visible in the differential image, suggesting that Mn is uniformly distributed in the film. The images shown on the top panel are for a GaMnN sample with 5.0% Mn grown by MBE using H_2/N_2 plasma as published previously (APL **80**, 4139 (2002)). The field of view (diameter across the image) is 62 μm for all images. Multiple images have been taken over different areas of the sample and the images shown are a good representative. Note that this PEEM microscope has a resolution of 100 nm, so features in the order of a few nm cannot be resolved. However, thorough high-resolution TEM experiments on samples grown using the same conditions indicate that there were no nm-scale features. Hence we conclude that Mn has incorporated into the GaN lattice uniformly.

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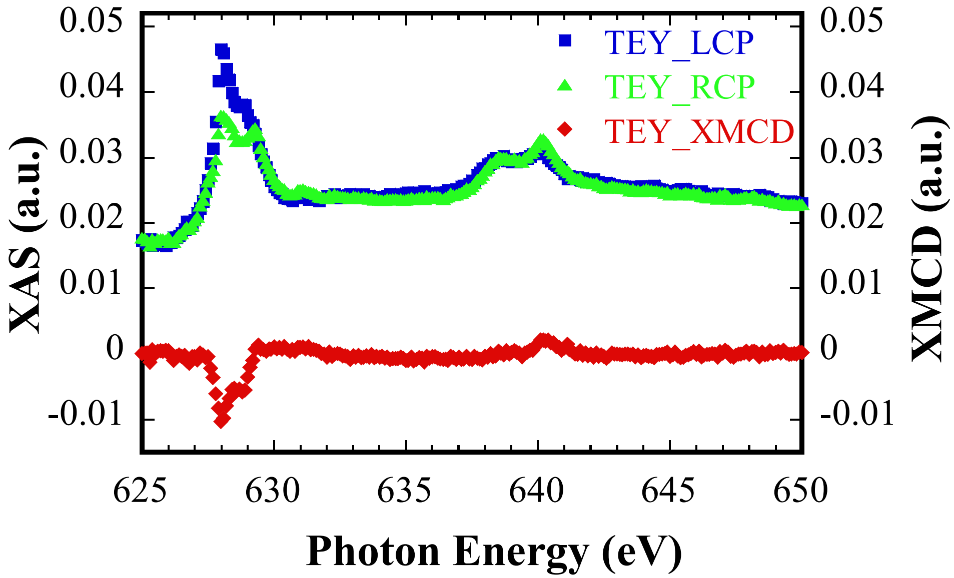
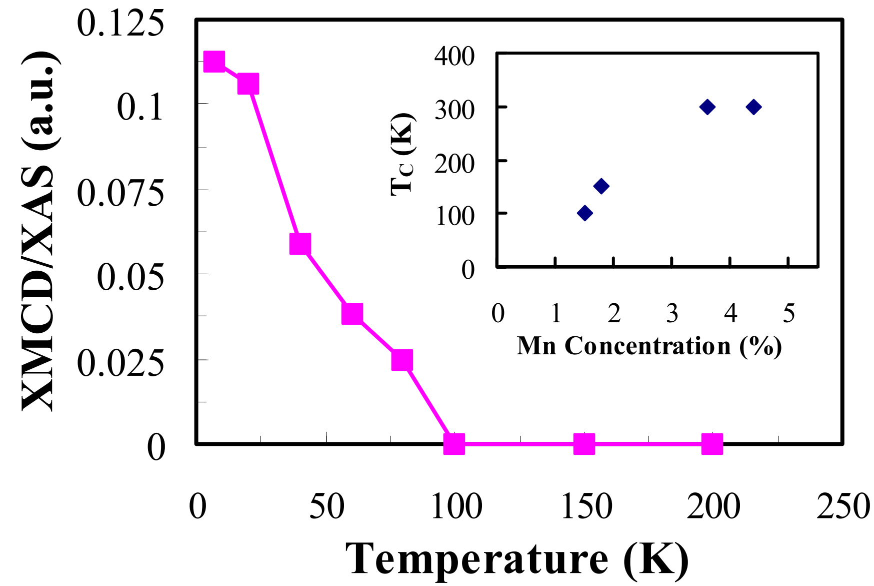


Electron yield at the *Mn* L_3 edge for a $Ga_{0.985}Mn_{0.015}N$ sample in 2 Tesla at 7 K. The red curve is the x-ray magnetic circular dichroism (XMCD) determined by subtracting the total electron yield (TEY) produced by the right circularly polarized (RCP) x-rays (green curve) from that of the left (LCP) (blue curve). A 20% difference is clearly present in the XMCD, indicating ferromagnetic ordering.



XMCD as a function of temperature for the same sample, indicating that T_c is 100 K. Inset: The dependence of T_c on Mn concentration, showing that it increases with Mn% with films containing more than 3.5% Mn exhibiting T_c greater than 300 K.

What: We have demonstrated that GaMnN films grown by plasma assisted MBE using H_2/N_2 pass one of the most important litmus tests for homogeneous FMS, that the T_c increases with Mn concentration. In addition, T_c is greater than 300 K for Mn incorporation larger than 3.5%, critical for practical spintronic applications.

Future: Examine the nature of Mn incorporation sites (substitutional or interstitial) by first principle calculations combined with spatially resolved x-ray absorption spectroscopy and XMCD measurements.

We have examined the magnetic properties of these homogeneous films by x-ray magnetic circular dichroism (XMCD). The electron yield at the *Mn* L_3 edge for a sample with 1.5% Mn is measured in a magnetic field of 2 Tesla at 7 K (left figure). The blue and green curves are the total electron yields (TEY) produced by the left and right circularly polarized (LCP and RCP) x-rays, respectively. The red curve is the XMCD determined by subtracting the TEY_RCP from the TEY_LCP. A 20% difference is clearly present, indicating that this GaMnN sample is ferromagnetic. By measuring the XMCD signal as a function of temperature, the Curie temperature (T_c) for this sample is determined to be 100 K, as shown in the right figure.

We've done similar experiments systematically on a series of samples with different Mn concentrations. Thereby we have demonstrated that these GaMnN films grown by plasma-assisted MBE using H_2/N_2 pass one of the most important litmus test for homogeneous FMS, that the Curie temperature (T_c) increases with Mn concentration, with films containing more than 3.5% Mn exhibiting T_c greater than 300 K (insert in the right figure). Hence these materials show great promise for practical spintronic devices.

To resolve if Mn are incorporated at substitutional sites or otherwise, first principle calculations are underway to compare the energetics of Mn incorporation at various substitutional and interstitial sites. Additional beam time has been reserved at APS in October to conduct further spatially resolved x-ray absorption spectroscopy and XMCD measurements. The knowledge of the nature of Mn incorporation, combined with total magnetization obtained using SQUID, will enable us to determine the magnetic moment per Mn atom and hence the active Mn concentration.

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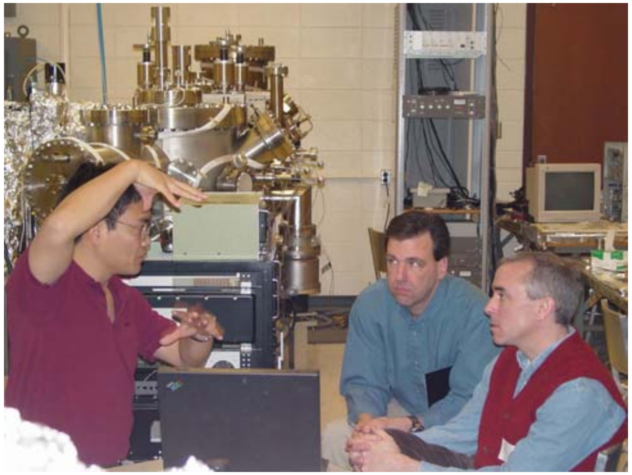
Education:

Two graduate students (Michael Harland and Seth King), one postdoctoral associate (Irene Cheung), and one undergraduate student (Dustin Kreft) contributed to this work. Michael was one of the 58 physics graduate students nationwide to receive an Award to attend the 54^{th} Meeting of Nobel Laureates in Lindau, Germany, June 27-July 2, 2004.

Michael is discussing with Laureate Richardson methods to reduce noises in high resolution imaging using atomic force microscope at the Lindau Meeting.

Outreach:

The Physics Department at the University of Wisconsin-Milwaukee houses an NSF Research Experiences for Teachers (RET) site, which provides new opportunities for high school physics teachers from southeastern Wisconsin and Milwaukee Public Schools. RET provides summer internships for these teachers to work directly with faculty and postdocs on various research projects of their choice.



The PI explains his research in spintronics to two teachers in his MBE lab during the open house for the RET program.